Review of Thickness-Shear Mode Quartz Resonator Sensors for Temperature and Pressure

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***Abstract*—This work reviews the use of thickness shear mode resonators for temperature sensing and pressure measurement. Advantages of such sensors include inherently digital format, high resolution, high accuracy, and long-term stability. This work reviews the physical principles involved in the operation of the devices along with quoted sensor performance results.**

The earliest commercially available temperature sensors were stand-alone units. Their use and commercial success evolved through different stages depending in part on ancillary electronics available at the time.

A number of temperature-sensing applications are ancillary to other thickness shear resonator sensors. Two main categories are separate resonator for temperature compensation and dual-mode operation of a single thickness shear resonator. Dual-mode operation subdivides into use of two modes from different thickness shear mode families or two modes from the same thickness shear mode family.

A variety of pressure sensors use the fact that the frequency of a thickness shear resonator changes with stress bias. Such applications divide conveniently into categories dependent on the pattern of stress bias used.

***Index Terms*—Piezoelectric resonators, pressure measurement, quartz, quartz resonator transducers, resonators, temperature measurement, transducers.**

I. Introduction

EERNISSE *et al.*[1] reviewed the entire field of quartz bulk resonator sensors in 1988. That paper reviewed several types of bulk acoustic wave (BAW) quartz resonators, such as thickness-shear, torsional, and flexure, for sensing physical parameters. Sensor applications included temperature, pressure, force, acceleration, fluid density, and thin-film thickness monitors. In 1995, Benes *et al.* [2] reviewed quartz resonator sensors, including an update of much of the same work, but extended the discussion to surface acoustic wave (SAW) devices for temperature, pressure, and chemoassay.

The present survey is not merely an update on these works. The purpose of this discussion is to highlight two of the most commercially successful families of quartz resonator sensors: thickness-shear mode resonators for sensing pressure and temperature.

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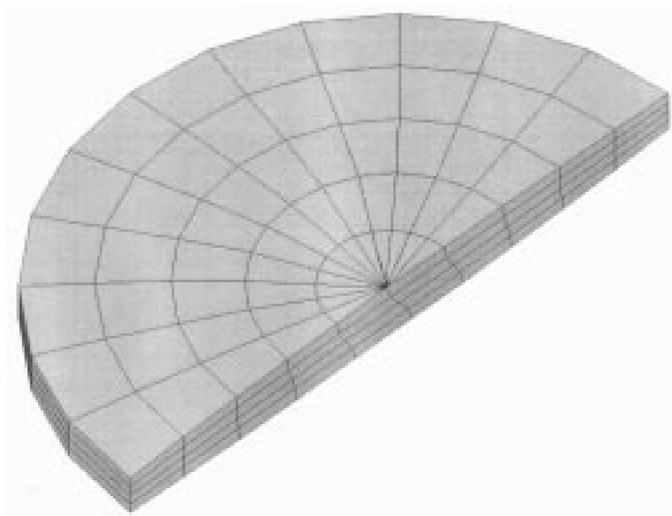


Fig. 1. Cross section through a circular TSMR showing the shear strain through the disc. Note the distortion is largest at the center and decays near the edges.

II. Mode Shape of Thickness Shear Mode Resonators

A thickness shear mode resonator (TSMR) consists of a plate (often circular) of crystalline quartz with thin-film metal electrodes deposited on the faces. The inverse piezoelectric effect is used to produce vibration in response to alternating voltages. For a thickness shear mode resonator, the crystallographic orientation of the disc is selected so that an electric potential applied through the thickness of the disc produces a shear stress.

The shape of a thickness shear fundamental vibrational mode is shown in Fig. 1. Note that the resonator blank is thicker in the middle, which causes the desired vibration to be concentrated in the center of the disc. This "energy trapping" makes it possible to support the resonator without introducing extraneous effects. In many applications, an overtone of the mode in Fig. 1 is used. Overtones also are "energy trapped." The dimensions, density, and stiffness of the quartz resonator determine the resonant frequency of vibration. Vibration can be driven at low power because of the low mechanical losses within the material. The resonator has high mechanical Q due to the energy trapping and the properties of quartz.

Many of the temperature sensor applications of a TSMR to be discussed here utilize a packaged resonator blank. Fig. 2 shows two typical versions of packaging, a two-point mount version and a three- or four-point mount version. The quartz resonator blank is held at the edges in these configurations to take advantage of the "energy trapping" for high Q. In addition, the

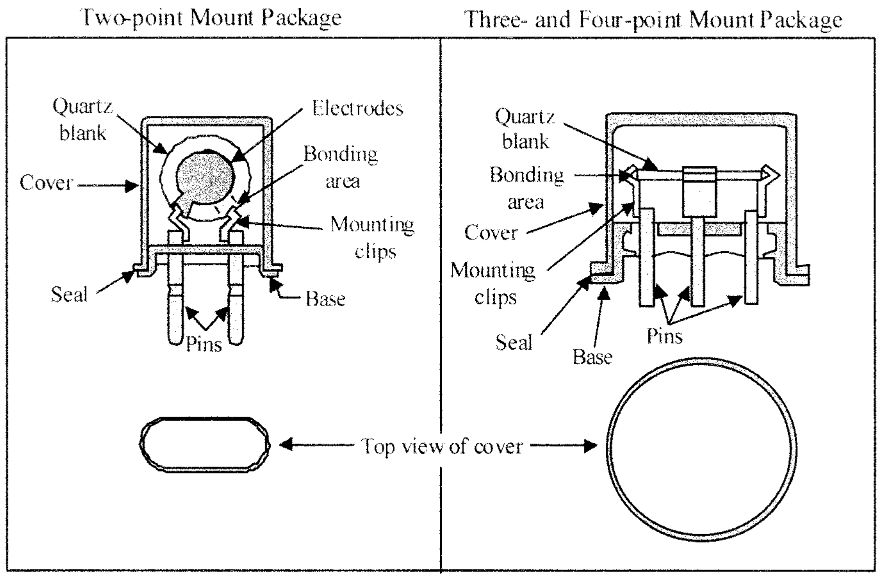


Fig. 2. Packaging for TSMRs using either a two-point mount or a three- or four-point mount.

TABLE I
STAND-ALONE TEMPERATURE SENSORS: COMPARISON OF SELECTED PERFORMANCE PARAMETERS

Author	References	Cut Family	Temperature range (°C)	Sensitivity (ppm/°C)	Frequency (MHz)
Wade, Slutsky	3	Y	-200 to 160	100	10
Smith, Spencer	4	Y	-20 to 100	80	5
Hammond	5,6	LC	0 to 200	48	20.8
Borissov, Spassov	7,8,9	LC	-60 to 280	38	26.5
Nakazawa	10—12	LC/SC	-160 to 180	60/14	11.2
Ziegler	15	Y (AC) LC	-25 to 75 -25 to 75	67 60	4.194304 13.56
Spassov	8,9	Y	-40 to 120	35	29.3

package is evacuated to obtain the highest possible Q. Most applications of a TSMR for pressure measurement utilize specialized shapes to be discussed later.

A crystal oscillator using a TSMR offers stability, low power, and frequency output. These properties, essential for frequency control applications, are also beneficial in sensing. Frequency can be measured with more resolution than any other parameter. Frequency is a “portable” standard; traceability to national atomic clocks can be obtained by NIST broadcast signals, or, more recently, from GPS satellite receivers. Laboratory instruments can be synchronized to these standards in real-time, avoiding downtime for instrument calibration, and eliminating accumulated error between calibrations.

III. STAND-ALONE TEMPERATURE SENSORS

Attempts to find TSMR cuts (crystallographic orientations) with minimal temperature sensitivity for frequency control applications revealed cuts with large temperature sensitivities. Since the 1960s, these cuts have been investigated (Table I) for temperature sensing. The reader can refer to IEEE Standard on Piezoelectricity (IEEE Std 176-1978) for the definition of cuts of quartz. One initial objective was a high-resolution digital alternative to the standard resistance thermometer (which required a Mueller bridge and sensitive galvanometer.) The bridge method was operator dependent (poor repeatability), provided no digital output, and high resolution measurements required higher bridge currents which produced thermometer self heating.

A. Y Cuts

Early studies of Y cut TSMR temperature sensors demonstrated good resolution (0.001°C or better) and low power dissipation (thermometer self-heating). For high-resolution temperature measurement, the TSMR sensors output frequency could be mixed with the frequency of a stable reference crystal, enhancing the temperature sensitivity of the output signal. One limitation of the TSMR as a temperature sensor is that the thermal conduction must be through the crystal leads because the package is evacuated. Some investigators [3] felt it was “not likely that quartz crystal thermometers will exhibit the stability with respect to thermal cycling and thermal shock achieved by the best resistance thermometers.” Although later investigators [15] re-examined the Y cut temperature sensors when low cost digital circuits (for wristwatches) were widely available, the authors are not aware of any commercial products using Y cut TSMR temperature sensors.

B. Linear Cuts

The TSMR temperature sensors described above used Y cut crystals because they exhibit high sensitivity to temperature. Hammond *et al.* ([5], [6] and reviewed well in [2]) at Hewlett Packard were willing to accept a lower sensitivity in exchange for linearity: a linear sensor was the simplest way to provide a linear, digital output using the electronics of the 1960s. The LC cut, which they developed, showed 0.0092 °C linearity from 0 to 200 °C, and stability of 0.01 °C with repeated thermal cycling.

The HP thermometer occupied a small niche in the overall temperature sensor market from the late 1960s until the mid 1990s. It was commercially successful because it provided an easy-to-use, high-resolution digital output (including an IEEE-488 interface), and showed good thermal stability. But the probe diameter was relative large, limiting thermal response and the physical "fit" of a probe. (It was too large for standard water triple point cells, for example.) Eventually, the commercial demise of the HP Thermometer was due not to improvements in competitive resistive sensors, but because of other advances in electronics. Cheap digital circuits enabled linearized, high resolution digital outputs from resistive sensors with acceptable stability and faster thermal response, all at low cost. The HP thermometer was successful during a "window of opportunity," until other electronic temperature measurement systems were available.

C. Infrared Sensors

Sensing temperature increase due to infrared radiation is a special case of temperature sensing for which quartz TSMRs have been proposed. In this application, the response time is limited by the infrared absorption of the quartz, and not by the crystal packaging that limits response for conductive/convective sensors. Ziegler [16] examined a Y-cut TSMR with 92 ppm/°C sensitivity. Over the range of 50 to 400 °C, he investigated wavelengths from 5 to 10 μm. Detection limit was found to be 10^{-7} W. He found that thin resonators provide faster response, but thicker ones are more stable. The response time was 2.6 s; he suggested that cooling the crystal would improve response time.

Vig and Filler [17] proposed an array of infrared microsensors (in the 200 MHz to 1 GHz frequency range) with 1 μ°C sensitivity. At 1 GHz, the 1 μm thick (200 molecular layers) resonator would not be practical for frequency control because of aging. However, for this sensor application aging isn't important, since only sensitivity to dynamic change is required. They recommend NLSC or SC-cuts so that recycle time in a scanned array is short. TSMR IR sensors would not need cooling as other IR detectors do. Fabrication limitations (primarily wafer size and ease of fabrication) may compromise available performance. Hamrour [18] also investigated a TSMR IR detector. To date, the TSMR IR temperature sensor has not been commercialized.

IV. Ancillary Temperature Measurement, Separate Resonator

A. Pressure Sensors for Downhole

EerNisse and Ward [19], [20] developed a TSMR pressure sensor for Halliburton. This design included TSMR temperature and reference crystals in an all-quartz, pressure-proof package which is located in the pressure fluid. In production, the temperature sensor is a torsional tuning fork (TTF) quartz resonator; their patent also envisioned the use of a dual-mode TSMR for pressure and temperature. Dennis and Totty [20] proposed replacing the TTF in the original Halliburton design with an AC-cut TSMR temperature sensor, suggesting that the AC-cut crystal extended the operating temperature range.

The Quartzdyne Pressure Transducer, as described by Ward and Wiggins [21], specifies three TSMR crystals: a pressure sensor (described below) in the pressure fluid, accompanied by temperature and reference crystals not in the pressure fluid. The temperature and reference crystals are packaged in typical TO-5 cans (see Fig. 2, four-point mount), which are thermally coupled to the pressure crystal by the metalwork of the assembly. The reference crystal signal (7.2 MHz) is mixed with both sensor frequencies to produce two low frequency (20–75 kHz) output signals. An interesting feature of this design is that the temperature sensor is used for digital temperature compensation of both the pressure and reference crystals. The temperature-compensated reference crystal can be used to count both low frequency signals.

Wiggins [23] sought to improve the thermal transient response of the original Quartzdyne transducer with the thermally matched compensation (TMC) design. This retained the pressure and reference crystals of [22], but created a pressure-proof temperature sensor, which is in the pressure fluid, adjacent to the pressure sensor. In addition to proximity, the advantage claimed was that the pressure and temperature sensors are structurally similar, so the thermal response times of the two sensors are well matched. Unlike the earlier approach [21], the mounting structure of the temperature sensor makes it pressure sensitive. Thus, two sensors are pressure and temperature sensitive, but one is much more sensitive to pressure, the other much more sensitive to temperature.

The use of TSMR temperature sensors in the Halliburton and Quartzdyne developments is not because of an inherent advantage of the TSMR temperature sensor, but because of "system" benefit. When a system already has a TSMR pressure sensor and reference crystal, adding a third TSMR and oscillator is a simple way to provide very high resolution temperature sensing. If a resistance temperature sensor were used, the analog/digital circuitry would add significant complexity and cost. With these advantages, TSMR temperature sensors are commercially successful; the stand-alone TSMR temperature sensors lack these advantages, and, as mentioned above, have been eclipsed by resistance temperature sensors with cheap digital electronics.

B. Temperature Compensation of Thin-Film Deposition Monitors

Way [24] proposed the use of three TSMRs for monitoring thin-film deposition. EerNisse [25] previously noted that the AT-cut and BT-cut provide nearly equal, but opposite, sensitivities to film stress, allowing mass and stress effects to be separated. Way chose to add an SC-cut crystal as a temperature sensor. The SC cut is not temperature sensitive enough for many applications, but the SC cut's insensitivity to film stress makes it ideal for this application. Way noted that the SC cut's temperature sensitivity is similar to the AT cut, with 40 °C difference in the inflection temperature; this difference provides enough sensitivity for temperature compensation. Although TSMRs are extensively used as thin-film deposition monitors, Way's method of temperature compensation has not been commercialized.

V. Ancillary Temperature Measurements for Frequency Control

Another commercially successful application of TSMR temperature sensors is in improving the stability of TSMR frequency standards. As in the pressure sensor applications above, the TSMR temperature sensor is used to correct temperature-induced errors in another frequency source. In the frequency control applications, the temperature sensor frequency may be produced by the timebase resonator (the "dual-mode" approach), or by an adjacent quartz device: various methods are described below.

A. Dual Mode (Two Different Mode Families)

Kusters *et al.* [26] demonstrated temperature compensation of SC-cut frequency control crystals, using the difference between the C mode (the desired slow-shear mode) and the more temperature-sensitive B mode (fast shear mode). They achieved temperature compensation of 1 ppb from −20 to 80 °C. During temperature changes of 15 °C/min, compensation of 0.01 ppm was maintained. They found that an oscillator with a single gain element and a single feedback path could drive both modes simultaneously. The circuit provides both mode frequencies, and the sum and difference frequencies as outputs.

Abramson [27] and Kosykh *et al.* [28] applied the method suggested by Kusters, and found that the temperature compensation of the SC-cut C mode is limited by B mode activity dips.

B. Dual Mode (Two Modes From The Same Mode Family)

Schodowski [29], [30] proposed the use of two harmonically-related C modes for temperature compensation of the SC cuts, while avoiding the activity dips of the B mode over a broad temperature range. His preferred method for temperature sensing uses the difference between the third overtone frequency, and three times the fundamental frequency.

Filler and Vig [31] demonstrated SC-cut crystals with well-behaved performance on two C modes, necessary for the implementation of a microprocessor-controlled crystal oscillator (MCXO) based on Schodowski's design. They showed that this MCXO would be free from activity dips, providing stability of a few parts in 10^8 over a −55 to 85 °C temperature range. There is ongoing development of the MCXO, as this approach continues to show promise.

VI. Ancillary Temperature Measurements for Sensors (Dual Mode)

EerNisse and Ward [32] suggested the use of the fundamental and an overtone of the same mode for temperature compensation of a TMSR sensor. Again, this is a "dual-mode" device since the temperature sensor frequency is produced in the actual TSMR being compensated. Both modes are sensitive to the physical parameter (such as force) being measured, with the two modes having different sensitivities to temperature.

Valdois *et al.* [33] and Sinha [34], building upon the SC-cut, found and experimentally verified a cut which is stress compensated in the B mode, and temperature compensated in the C mode. This cut is labeled the SBTC-cut. Envisioned uses included a dual-mode temperature-compensated pressure sensor, and time base crystals with both stress and temperature compensation at the turning point temperature.

Using theoretical models by Sinha [34], Besson *et al.* [35] developed two dual-mode pressure sensor designs: the SBTC and one which became the Schlumberger CQG. They recommended these quartz TSMR sensors for downhole use due to strength, long-term stability, and freedom from hysteresis. Besson noted that the existing pressure sensors employed a separate temperature sensor.

Dulmet *et al.* [36] reported on a dual-mode SC-cut TSMR force sensor, using the fifth overtone of the C mode and the third overtone of the B mode. They demonstrated force sensors with relative accuracy of 10^{-2} to 10^{-3} in the 0–80 °C range.

Pierce *et al.* [37] used a dual-mode SC-cut as a temperature-compensated microbalance (film thickness monitor). The SC-cut was chosen because it is compensated for film stress changes [13], and for thermal transients [14]; it is also relatively free of activity dips, and has low drive level sensitivity. The authors used the fundamental and third overtones of the C mode. Film thickness sensitivity in the sub-monolayer range was demonstrated in a UV-ozone cleaning process, the dual mode operation provided temperature compensation during a 3–5 °C/min (25 to 60 °C) temperature ramp.

VII. Pressure Sensors

A. Pressure Sensors Using Diametric Force Application

Squeezing on a diameter of a TSMR disc aligned along the X crystallographic direction causes an AT-cut resonator to increase in frequency, while a BT-cut resonator decreases in frequency [38]. Detailed measurements were carried out in the 1960s and 1970s by Ballato and Bechmann [39], Ratajski [40], and Dauwalter [41]. Ballato *et al.* [42] and Janiaud [43] thoroughly characterized the effect theoretically. These frequency shifts, due to a static stress bias, occur due to nonlinear effects acting through the third-order elastic stiffness coefficients. The stress pattern in the center of the resonator disc is compressive along the axis of force application and tensile orthogonal to the axis of force application. Some effects of the anisotropy of quartz were noted, especially for the AT-cut [42], [43]. EerNisse [44] examined the temperature behavior of the effect experimentally for a variety of resonator cuts.

Corbett [45] proposed this diametric force effect in the AT-cut for force and pressure measurements, where a surrounding structure squeezes on a diameter of a disc. In the case of pressure measurements, force is generated by pressure acting on a metal diaphragm. He shows a variety of schemes to try to overcome temperature effects from differences in thermal expansion in the structure. Force from the diaphragm is transferred to the disc via a spring and pushrod arrangement. Several structures are discussed to minimize hysteresis and

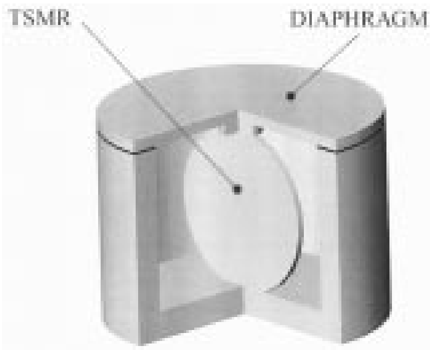


Fig. 3. Structure where external hydrostatic pressure applies a diametric force to a TSMR disc via a quartz diaphragm (Hewlett Packard).

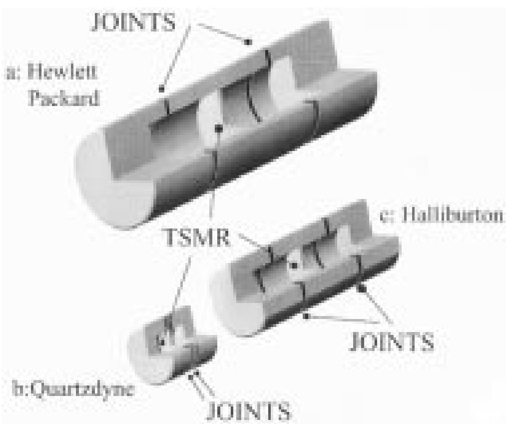


Fig. 4. Structures where external hydrostatic pressure applies planar stress patterns in a TSMR disc via a cylindrical shell. (a) Uniform radial stress (Hewlett Packard). (b) Uniform radial stress (Quartzdyne). (c) Superposition of diametric force effect and uniform radial stress from the presence of deep flats (Halliburton).

nonreproducibility caused by the pushrod contact with the edge of the disc.

Karrer and Ward [46] constructed an all-quartz structure to measure pressure. A quartz diaphragm squeezes on a diameter of an AT-cut resonator as seen in Fig. 3. The crystallographic direction of the force axis is the X crystal axis, which has the largest diametric force effect on frequency. The all-quartz structure avoids differences in thermal expansion. Force is carried from the diaphragm and base to the disc edges by devitrifying glass joints. The resonator was a 3 MHz fundamental AT-cut operated on the fifth overtone for good energy trapping. Frequency shift with pressure is 10 Hz/kPa (1.5 Hz/psi). The resolution reported was 0.0003% of the 2×10^5 Pa (29 psi) full scale. Drift and zero returns from nonelastic effects were less than 0.01% of full scale at room temperature over periods of weeks.

B. Pressure Sensors Using Uniform Stress

Interest in higher pressure ranges found in oceanographic applications and oil and gas exploration and production led to a structure where the resonator disc is squeezed uniformly around the perimeter. Karrer and Leach [47] and Hammond and Benjaminson [48] at Hewlett Packard, HP, used the geometry shown in Fig. 4(a). Their design incorporated an integral shell to move the joint far enough away from the resonator to minimize effects of joint instability. The structure is closed with two end caps as seen in Fig. 4(a). The joining of the three parts is done with devitrifying glass. Electrical contacts to the electrodes on the resonator disc are made via metal tabs that pass through the glass joints. As pressure outside the structure compresses the cylindrical shell, a uniform radial stress two to three times the applied pressure occurs in the resonator.

This HP device uses a BT-cut resonator, which exhibits a scale factor of frequency versus pressure relatively independent of temperature. This was an important feature because the data processing electronics of that period lacked the microprocessor power to correct for this effect. Static temperature effects on the frequency are compensated by mixing the output signal of the pressure oscillator with a BT-cut resonator oscillator matched in terms of static frequency versus temperature and packaged as seen in Fig. 2 for the four-point mount. The resulting system had no independent temperature measurement and suffered from large pressure errors during thermal transients.

Some of the sensor details can be found in Table II. This system resolves 69 Pa (0.01 lb/in^2) with a 1 s gate time. Overall accuracy was 0.01% of full scale up to 150 °C. This accuracy approaches the limit of accuracy for pressure as traceable to primary standards at NIST. Kusters and Kaitz [49] and Kaitz [50] performed quartz material studies that extended the performance range to 10.4×10^7 Pa (15 000 lb/in^2) and 200 °C. Some improvement was seen using natural quartz compared to cultured quartz.

In the early 1990s, Quartzdyne, Inc. recognized the need for a quartz resonator pressure sensor for oil and gas exploration and production that was both cheaper to manufacture and smaller in size to speed up response to thermal transient conditions (see Ward and Wiggins [22]). Microprocessors were readily available by this timeframe, so an independent temperature measurement could be used for temperature compensation. EerNisse and Ward [51] chose a simpler geometry to reduce manufacturing costs. As seen in Fig. 4(b), the geometry is simply a resonator disc with end caps attached to both major surfaces. The joints have been moved to the TSMR surfaces, as seen in Fig. 4b. Fabrication techniques are similar to the HP device. The cost of manufacturing dropped dramatically with only a small sacrifice in long-term drift performance. The device uses an AT-cut resonator to obtain a large scale factor for frequency versus pressure [51]. The AT-cut can maintain a high Q with a relatively small diameter to thickness ratio, so the size of this device is only 1.46 cm outside diameter. The smaller size improves the response time to transient pressure and temperature situations and allows use of bellows to isolate the pressure sensor from the corrosive gases and liquids in oil and gas wells. Temperature compensation is accomplished as discussed in earlier sections of this paper using a separate quartz resonator for temperature measurement.

Pressure sensor details are found in Table II. The resolution of this three TSMR system is typically 23 Pa (0.003 lb/in^2). Useable resolution is limited in part by the effectiveness of the temperature compensation and by the calculational accuracy in the algorithms used for the temperature corrections. Accuracy attained is better than 0.02% of full scale. Presently, devices

TABLE II
COMMRECIALIZED TSMR PRESSURE SENSORS; COMPARISON OF SOME SELECTED PERFORMANCE PARAMETERS

Company	Refs.	Stress Pattern (Crystal Cut)	Typical Full Scale (10^3 kPa) (psi)	Typical Maximum Temp. (C)	Pressure Sensitivity Of Frequency (ppm/kPa)	Pressure Frequency (MHz) Overtone
Hewlett Packard	47-50	Uniform Radial (BT)	76 11,000	150	2	5 3rd
Quartzdyne	22, 51-54	Uniform Radial (AT)	110 16,000	175	2	7.2 3rd
Halliburton	57-60	Uniform Radial + Dia-metric (AT)	110 16,000	175	3.5	3.6 5th
Schlumberger	35, 36, 61, 62	Uniaxial (Proprietary)	110 16,000	175	1.6	5.15 3rd

are manufactured with equivalent performance to 1.4×10^8 Pa (20 000 psi) full scale up to 200 °C. Transducers using this technology are found all over the world in oil and gas exploration and production, including measurement while drilling, open-hole and cased-hole well logging, production monitoring, and permanent installations in producing wells.

EerNisse and Ward [51] and Clayton and EerNisse [52] used this shape to explore the behavior of quartz, such as Dauphiné twinning threshholds, under conditions of high stress and temperatures [51], [52]. Clayton and EerNisse [53], [54] used finite element analysis to design sensors with end caps of a reentrant shape to increase sensitivity and avoid twinning problems.

The structures mentioned thus far for uniform stress in the resonator are best suited for higher pressure ranges because of the stiffness of the cylindrical shells. One approach for using uniform stress in a resonator for lower pressures has been patented by Frishe *et al.* [55]. This structure uses the resonator disc as a diaphragm so that unequal pressure between the two major surfaces causes membrane-stretching stresses. A second matched resonator disc with equal pressure on both sides is used to compensate for static frequency versus temperature effects.

Ramm and Formaz [56] propose another method for using uniform stress that incorporates a ring-electroded resonator disc where energy trapping occurs in a ring around the center of the disc. Force is applied with a pushrod in the center of the disc. Since the perimeter of the resonator disc is clamped, uniform membrane and bending stresses occur, which change the TSMR frequency.

C. Pressure Sensors Using Uniform Stress and a Diametric Force Component

Pressure sensors with uniform stress were limited in design options to one degree of freedom, the crystallographic orientation of the resonator. EerNisse and coworkers [57]–[60] recognized in the 1980s that use of nonuniform stress in the resonator would provide an additional degree of freedom for optimizing sensor performance. A structure used by Halliburton in oil and gas exploration and production today is shown in Fig. 4(c). Flats are added to break up the symmetry of the shell surrounding the resonator disc. The structure is closed with two end caps and the joints are far from the TSMR as seen in Fig. 4(c). Fabrication techniques are similar to the HP device. The result of applying pressure to this structure is a nonuniform stress in the resonator disc. The major stress in the resonator is along the flat axis where the walls of the shell are thinnest. The minor stress (still compressive) is orthogonal to the flat axis where the walls of the shell are thickest. The net result is an additional degree of freedom by choosing the crystallographic orientation of the flat axis.

The parameter chosen for optimization was the temperature dependence of scale factor. The effect is defined as the fractional change in scale factor with temperature. This parameter is as large as 1000 ppm/°C for the AT-cut with uniform stress [57]. This parameter was intentionally minimized in the uniform stress sensors of HP by using the BT-cut device, as mentioned above. In the present case, the ratio of stress along the flat axis to stress orthogonal to the flat axis can be increased by increasing the flat depth. Thus, the flat depth becomes another design degree of freedom. EerNisse [57] developed an analysis technique that superimposed a diametric stress effect with a uniform stress effect. Use was made of published experimental results on the temperature dependence of the diametric force effect [44]. Depending on the crystallographic orientation of the flats, the diametric force effect increased or decreased the temperature dependence of the scale factor. The optimum crystallographic orientation for the flat axis for the AT-cut was found to be along the X crystal axis. The analytical results agreed well with experimental data from sensors with different flat depths. The fractional change in scale factor with temperature could be reduced to 250 ppm/°C [57]. A side benefit is that the pressure sensitivity increases as well. Temperature compensation for this sensor is accomplished with a separate resonator for temperature measurement as discussed above.

Pressure sensor details are found in Table II. The resolution of this three TSMR system is typically 23 Pa (0.003 lb/in^2). Again, resolution is limited in part by the accuracy of the temperature measurement and by the calculation accuracy in the algorithms used for the temperature corrections. Accuracy attained is better than 0.01% of full scale up to 175°C. Ward and EerNisse [58] noted some improvement in performance in terms of hysteresis using natural quartz instead of cultured quartz.

D. Pressure Sensors Using Uniaxial Stress

Another choice for a stress pattern is uniaxial. This stress pattern is generated in a sensor used extensively in oil and gas exploration and production by Schlumberger. The structure, called the CQG and proposed by Besson *et al.*, [35] is shown in Fig. 5. The resonator plate is rectangular and is contoured for energy trapping. The resonator plate is formed integral to, and suspended across a diameter, of a cylindrical shell [61], [62], but the normal of the plate is orthogonal to the axis of the cylinder. The shell is closed with endcaps as seen in Fig. 3. Fabrication techniques are similar to the HP device. The use of a unaxial stress requires choice of a crystallographic orientation that has large force sensitivity for uniaxial stress. Two possible crystallographic orientations are discussed by Dulmet, *et al.* [36]. The AT-cut has its largest sensitivity along the X crystallographic axis and the SC-cut has its largest force sensitivity at an angle near 50° from the X' plate axis. This sensor uses a dual-mode approach for temperature compensation as discussed above.

Pressure sensor details are found in Table II. The resolution of this system is quoted as 7 Pa (0.001 lb/in^2) with a 1 s gate time. Accuracy attained is better than 0.01% of full scale up to 175 °C. Although the temperature measurement and pressure measurement are co-located [35], [61], [62], some errors still occur in transient temperature conditions because of stresses from the thermal gradients existing throughout the structure. Some of this effect can be compensated for in the data processing [61], [62]. Recently, Matsumoto *et al.* [62] extended the pressure range and temperature range of this sensor concept with the help of finite element analysis. Prototypes have been tested to 175 Mpa (25 500 lb/in^2) and 180 °C without twinning.

Another structure for obtaining approximately uniaxial stress in a resonator disc is described by Delaite [63]. This structure uses force application over diametrically opposed peripheral zones to avoid high stress concentration. The structure could be accomplished in practice by using the geometries in Fig. 4(a)–(c) by cutting slots in the resonator disc similar to those used in the BVA resonator used for frequency control by Besson [64].

VIII. Summary

This review covered the use of TSMRs as sensors for temperature and pressure. Temperature sensors, both as stand-alone temperature sensors and as temperature measurements ancillary to other TSMR sensors, have had mixed commercial success even though they exhibit high resolution and accuracy. Single-mode operation is typical for stand-alone applications. At the present time, there are no significant commercial products for stand-alone temperature sensors. Both single-mode and dual-mode operation are utilized for ancillary temperature sensing. There are several successful commercial applications for ancillary temperature sensors.

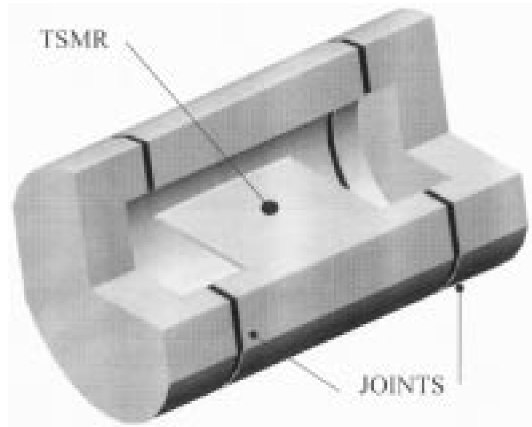


Fig. 5. Structure where external hydrostatic pressure applies a uniaxial stress in a TSMR plate via a cylindrical shell (Schlumberger).

Pressure sensors have been highly successful in oil and gas exploration and production because of their high resolution and accuracy and because of their ability to withstand the high pressures and temperatures in oil and gas wells. The plate geometry of the TSMR generally restricts its use to higher pressure ranges where large forces can be used to shift the resonant frequency. Both single-mode and dual-mode operation are used for pressure sensing applications. All of the commercially available versions perform comparably in general.

Future developments for TSMR temperature and pressure sensors are limited presently by the narrow market niches they serve. Both the higher temperatures and higher pressures being found in newer fields by the oil and gas industry present challenges in maintaining the performance expected from these sensors. Considerable on-going research is focused on measuring higher pressures and temperatures while avoiding twinning in the TSMR. In addition, efforts are focused on reducing long-term drift in the presence of the higher pressures and temperatures. All of the research to date is on quartz material; no other stable piezoelectric material has been developed to the point of being a candidate to replace quartz in pressure sensor applications.

References

[1] E. EerNisse, R. Ward, and R. Wiggins, "Survey of quartz bulk resonator sensor technologies," *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, vol. 35, pp. 323–330, 1988.
[2] E. Benes, M. Gröschl, W. Burger, and M. Schmid, "Sensors based on piezoelectric resonators," *Sens. Actuators A*, vol. 48, no. 1, 1995.
[3] W. H. Wade and L. J. Slutsky, "Quartz crystal thermometer," *Rev. Sci. Instrum.*, vol. 33, pp. 212–213, 1962.
[4] W. Smith and W. Spencer, "Quartz crystal thermometer for measuring temperature deviations in the 10^{-3} to 10^{-6} °C range," *Rev. Sci. Instrum.*, vol. 34, pp. 268–270, 1963.
[5] D. Hammond and A. Benjaminson, "Linear quartz thermometer," *Instrum. Contr. Syst.*, vol. 38, p. 115, 1962.
[6] D. Hammond, C. Adams, and P. Schmidt, "A linear quartz crystal temperature sensing element," *ISA Trans.*, vol. 4, pp. 349–354, 1965.
[7] M. Borissov, A. Balabanova, E. Radeva, L. Spassov, and E. Yosiffov, "New cut of a quartz resonator with a linear temperature frequency characteristic," *Electron. Lett.*, vol. 23, pp. 169–171, 1987.
[8] L. Spassov, "Piezoelectric quartz resonators as highly sensitive temperature sensors," *Sens. Actuators A*, vol. 30, pp. 67–72, 1992.
[9] L. Spassov, L. Yossiffov, E. Georgiev, and L. Vergov, "A rotated Y-cut quartz resonator with a linear temperature-frequency characteristic," *Sens. Actuators A*, vol. 58, pp. 185–189, 1997.

[10] M. Nakazawa, H. Yamaguchi, A. Ballato, and T. Lukaszek, "Stress-compensated quartz resonators having ultra-linear frequency–temperature responses," in *Proc. 38th Annu. Freq. Contr. Symp.*, 1984, pp. 240–245.

[11] M. Nakazawa, T. Takemae, A. Miyahara, and K. Matsuyama, "A study of quartz temperature sensors characterized by ultralinear frequency–temperature response," *IEEE Trans. Son. Ultrason.*, vol. SU-32, pp. 828–834, 1985.

[12] M. Nakazawa, A. Ballato, and T. Lukaszek, "Studies of stress compensated quartz resonators with ultralinear frequency–temperature responses," *J. Appl. Phys.*, vol. 60, pp. 3765–3771, 1986.

[13] E. EerNisse, "Quartz resonator frequency shifts arising from electrode stress," in *Proc. 29th Annu. Freq. Contr. Symp.*, 1976, pp. 141–156.

[14] J. Kusters, "Transient thermal compensation for quartz resonators," *IEEE Trans. Sonics Ultrason.*, vol. SU-23, pp. 273–276, 1976.

[15] H. Ziegler, "A low-cost digital temperature sensor system," *Sens. Actuators*, vol. 5, pp. 169–178, 1984.

[16] H. Ziegler and J. Tiesmeyer, "Digital sensor for IR radiation," *Sens. Actuators*, vol. 4, pp. 363–367, 1984.

[17] J. Vig, R. Filler, and Y. Kim, "Uncooled IR imaging array based on quartz microresonators," *J.. Microelectromech. Syst.*, vol. 5, pp. 131–137, 1996.

[18] M. Hamrour, S. Galliou, and B. Dulmet, "A new type of infrared-sensitive resonator used as a thermal senso," *Sens. Actuators A*, vol. 65, pp. 147–151, 1998.

[19] E. EerNisse and R. Ward, "Transducer and sensor apparatus and method," U.S. Patent 4 802 370, 1989.

[20] ——, "Transducer and sensor apparatus and method," U.S. Patent 4 936 147, 1990.

[21] J. Dennis and C. Totty, "Crystalline transducer with AC-cut temperature crystal," U.S. Patent 5 299 868, 1994.

[22] R. Ward and R. Wiggins, "Pressure transducer assembly," U.S. Patent 5 231 880, 1993.

[23] R. Wiggins, "Quartz thickness-shear mode resonator temperature-compensated pressure transducer with matching thermal time constants of pressure and temperature sensors," U.S. Patent 5 471 882, 1995.

[24] S. Way, "Quartz resonator techniques for simultaneous measurement of areal mass density, lateral stress, and temperature in thin films," *Vacuum*, vol. 44, pp. 385–388, 1993.

[25] E. EerNisse, "Simultaneous thin film stress and mass change measurements using quartz resonators," *J. Appl. Phys.*, vol. 43, pp. 1330–1334, 1972.

[26] J. Kusters, M. Fischer, and J. Leach, "Dual mode operation of temperature and stress compensated crystals," in *Proc. 32nd Annu. Freq. Contr. Symp.*, 1978, pp. 389–397.

[27] I. V. Abramson, "Two-mode quartz resonators for digital temperature compensated quartz oscillators," in *Proc. 46th Annu. Freq. Contr. Symp.*, pp. 442–447.

[28] A. Kosykh, I. Abramson, and V. Begaev, "Dual mode oscillators with resonators excited on B and C modes," in *Proc. 1994 IEEE Int. Freq. Contr. Symp.*, 1994, pp. 578–586.

[29] S. Schodowski, "Resonator self-temperature-sensing using a dual-harmonic-mode crystal oscillator," in *Proc. 43rd Annu. Freq. Contr. Symp.*, 1989, pp. 2–7.

[30] ——, "Dual mode quartz thermometric sensing device," U.S. Patent 4 872 765, 1989.

[31] R. Filler and J. Vig, "Resonators for the microcomputer compensated crystal oscillator," in *Proc. 43rd Annu. Freq. Contr. Symp.*, 1989, pp. 8–15.

[32] E. EerNisse and R. Ward, "Resonator transducer system with temperature compensation," U.S. Patent 4 535 638, 1985.

[33] M. Valdois, B. Sinha, and J. Boy, "Experimental verification of stress compensation in the SBTC-cut," *IEEE Trans. Ultrasoni. Ferroelect. Freq. Contr.*, vol. 36, pp. 643–651, 1989.

[34] B. Sinha, "Stress compensated orientations for thickness-shear quartz resonators," in *Proc. 35th Annu. Frequency Control Symp.*, 1981, pp. 213–221.

[35] R. Besson, J. Boy, B. Glotin, Y. Jinzaki, B. Sinha, and M. Valdois, "A dual-mode thickness-shear quartz pressure sensor," *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, vol. 40, pp. 584–591, 1993.

[36] B. Dulmet, R. Bourquin, and N. Shibanova, "Frequency-output force sensor using a multimode doubly rotated quartz resonator," *Sens. Actuators A*, vol. 48, pp. 109–116, 1995.

[37] D. Pierce, Y. Kim, and J. Vig, "A temperature insensitive quartz microbalance," in *Proc. 1997 Int. Frequency Control Symposium*, 1997, pp. 41–48.

[38] V. Bottom, "Note on the anomalous thermal effect in quartz oscillator plates," *Amer. Mineral.*, vol. 32, pp. 11–12, 1947.

[39] A. Ballato and R. Bechmann, "Effect of initial stress in vibrating quartz plates," *Proc. IRE*, vol. 48, pp. 261–262, 1960.

[40] J. Ratajski, "Force–frequency coefficient of singly rotated vibrating quartz crystals," *IBM J.*, vol. 12, pp. 92–99, 1968.

[41] C. Dauwalter, "The temperature dependence of the force sensitivity of AT-cut quartz crystals," in *Proc. 26th Annu. Freq. Control Symp.*, 1972, pp. 108–112.

[42] A. Ballato, E. EerNisse, and T. Lukaszek, "The force–frequency effect in doubly rotated quartz resonators," in *Proc. 31st Annu. Freq. Contr. Symp.*, 1977, pp. 8–16.

[43] D. Janiaud, L. Nissim, and J. Gagnepain, "Analytical calculation of initial stress effects on anisotropic crystals: Application to quartz resonators," in *Proc. 32nd Annu. Freq. Contr. Symp.*, 1978, pp. 169–179.

[44] E. EerNisse, "Temperature dependence of the force–frequency effect for the AT-, FC-, SC-, and rotated X-cuts," in *Proc. 34th Annu. Freq. Contr. Symp.*, 1980, pp. 426–430.

[45] J. Corbett, "Crystal force and pressure transducers," U.S. Patent 5 424 598, Jun. 13, 1995.

[46] E. Karrer and R. Ward, "A low-range quartz resonator pressure transducer," *ISA Trans.*, vol. 16, pp. 90–98, 1977.

[47] H. Karrer and J. Leach, "A quartz resonator pressure transducer," *IEEE Trans. Ind. Electron. Contr. Instrum.*, vol. IECI-16, pp. 44–50, 1969.

[48] D. Hammond and A. Benjaminson, "The crystal resonator—A digital transducer," *IEEE Spectrum*, pp. 53–58, Apr. 1969.

[49] J. Kusters and G. Kaitz, "Characteristics of natural, swept natural, and cultured X- and Z-growth quartz material in high temperature high stress application," in *Proc. 39th Annu. Freq. Control Symp.*, 1985, pp. 223–233.

[50] G. Kaitz, "Extended pressure and temperature operation of BT-cut pressure transducers," in *Proc. 38th Annu. Freq. Control Symp.*, 1984, pp. 245–250.

[51] E. EerNisse and R. Ward, "Quartz resonator sensors in extreme environments," in *Proc. 45th Annu. Symp. Freq. Control*, 1991, pp. 254–260.

[52] L. Clayton and E. EerNisse, "Application of finite element analysis to the design of quartz thickness shear mode pressure sensors," in *Proc. IEEE Int. Frequency Control Symp.*, 1996, pp. 541–549.

[53] ——, "Quartz thickness-shear mode pressure sensor design for enhanced sensitivity," *IEEE Trans. Ultrason., Ferroelect. Freq. Contr.*, vol. 45, pp. 1196–1203, 1998.

[54] ——, "Quartz resonator frequency shifts using the finite-element method," *Int. J. Numer. Meth. Eng.*, vol. 36, pp. 385–401, 1993.

[55] R. Frishe, R. Dankwort, and C. Klem, "Vibrating quartz diaphragm pressure sensor," U.S. Patent 4 479 070, 1984.

[56] A. Ramm and J. Formaz, "Quartz resonating force and pressure transducer," U.S. Patent 4 644 804, 1987.

[57] E. EerNisse, "Theoretical modeling of quartz resonator pressure transducers," in *Proc. 41st Annu. Symp. Freq. Contr.*, 1987, pp. 339–343.

[58] R. Ward and E. EerNisse, "A reduced hysteresis extended range quartz pressure transducer," in *Proc. 41st Annu. Symp. Freq. Contr.*, 1987, pp. 344–349.

[59] E. EerNisse, "Resonator pressure transducer," U.S. Patent 4 550 610, 1985.

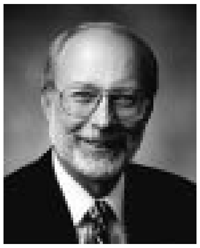
[60] J. Dennis and V. Zeller, "Quartz technology allows for wider downhole pressure testing range," in *Proc. Soc. Petroleum Eng. Production Oper. Symp.*, 1989, SPE 18 879, pp. 485–494.

[61] N. Matsumoto, Y. Sudo, B. Sinha, and M. Niwa, "Long-term stability and performance characteristics of crystal quartz gauge at high pressures and temperatures," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 47, pp. 346–354, 2000.

[62] N. Matsumoto, Y. Oohashi, M. Miyashita, G. Fujisawa, B. Sinha, and M. Niwa, "Development of a quartz pressure sensor for extreme hostile environment applications," in *Proc. 2000 EFTF*, Turin, Italy, 2000.

[63] R. Delaite, "Piezoelectric resonator with either minimal or extreme sensitivity to external pressure stresses," U.S. Patent 4 814 662, 1989.

[64] R. Besson, "A new 'electrodeless' resonator design," in *Proc. 31st Annu. Symp. Freq. Contr.*, 1977, pp. 147–152.



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